

Unsteady-state temperature field and sensitivity analysis of gear transmission



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ABSTRACT

This paper investigated three-dimensional analysis of unsteady-state temperature field and temperature sensitivity analysis of gear transmission, for which frictional heat caused surface temperature rise which reduced their bearing capacity and scuffing resistance. Unsteady-state temperature field of gear surface was analyzed, results providing continuous temperature distribution of any meshing moment and at any position on gear surface. Thermal sensitivity comparison considering different operating conditions and gear geometric parameters was given out. Flash temperature influenced by dynamic load was also provided. The thermal experiment validated the correctness of the model and analysis results. The numerical analysis and calculation results combined with experimental results offered evidence to improve gear scoring and scuffing capacity.

1. Introduction

With the rapid development of advanced manufacturing technology industry, tribology problems in special working condition, like high-speed heavy-load gear transmission, demand improvements [1]. The engaging of contact gears can sometimes generate a considerable amount of frictional heat, which acts as a periodical heat source that heats up gear surface temperature and forms a complex and heterogeneous temperature field. The temperature rise on the meshing faces often leads to the break of lubricating oil film. Metal surfaces no longer separated by the oil film tend to engage and adhere to each other before stripping off gear tooth as gears rotate [2–4]. Flash temperature affects gear tribological conditions and thus has an influence on the scoring that can be estimated and improved by the investigation of gear transmission unsteady-state temperature field and flash temperature. Unsteady state in this article, compared to steady state, equals to transient state.

As early as 1937, Blok [5] successfully obtained the approximate formula of transient contact temperature based on two-dimensional frictional heat flux formulas that came from relative sliding between two objects. Then he assumed the heat source to be moving at a constant speed and introduced the calculation formula of transient contact temperature of gears [6]. Later in 1963, the concept of flash temperature, which could predict the gear lubricating condition and prevent scoring, was brought up [7]. In 1974, Tobe and Kato looked into instantaneous contact temperature by further improving the partition of frictional heat

between engaging teeth [8]. Terauchil used an oscilloscope to measure gear surface temperature in order to improve numerical gear temperature analysis [9]. Further development of gear temperature field theory was made by Wang, Cheng [10], Patir [11] and Townsend [12], who investigated factors influencing gear temperature like convection coefficient, frictional heat flux and loads boundary conditions.

K.Mao investigated influential factors for gear temperature, for example heat partition between gear teeth, specific gear geometry and running speed, as applied to polymer composite gears, which were much more sensitive to temperature than conventional metal gears [13]. Furthermore, K.Mao analyzed heat transfer on gear surface and tooth body, revealing the spur gear flash temperature variation pattern [14]. T.Tevrus used both numerical and experimental methods for tooth profile temperature in order to predict scoring [15]. Gear temperature calculation can also be used to predict material hardness changes in grinding [16].

Chen and Liu analyzed steady-state temperature field of a crankcase by using fluid simulation method, which was inspirational [17]. In another study, factors influencing gear temperatures, like gear contact stress and relative sliding velocity were improved for more accurate analysis [18]. There are also some studies using finite element method to perform the meshing of gears along the line of action [19,20] that are of referential value to gear simulation analysis.

Both the gear transient temperature and flash temperature are significant means to evaluate gear scoring capacity. But in recent years,

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there are not many coupled studies of gear thermo-tribo or tribo-dynamic investigations worldwide, though which have begun to draw people's increasing attention. Lu [21] investigated thermal elastic hydrodynamic lubrications of gear systems. Sheng Li proposed formulation of gear mechanical power loss under thermal tribo-dynamic condition [22]. Then he gave the gear dynamics and tribological behavior model with a thermal mixed EHL (Elastic Hydrodynamic Lubrication) formulation coupled by a six DOF (Degree of Freedom) transverse-torsional discrete dynamics equation set to investigated flash temperature rises [23]. Li built dynamic model of the gear system, obtained dynamic differential equations considering time-varying stiffness, scuffing, profile error and misalignment [24]. Based on this, Xue further investigated the dynamic and thermo-elastic lubricating condition of gear system based on time-varying stiffness [25].

According to the latest researches, stationary fluid flows with heat exchanges have been considered in gear transmission temperature prediction, along with novel approaches to measure lubricating interface conditions [26,27]. Ronny Beilicke [28] researched the contact of tooth flanks of helical gear pairs using a transient three-dimensional thermal elastohydrodynamic calculation model. He suggested that Diamond-like Carbon (DLC) coating could influence friction between gears as well as gear temperature. S.M. Evans and P.S. Keogh used thermal experiments to analyze the temperature of aligned rod and running gears, and interestingly enough, their results can be used to assess gear thermal performance without testing full gear pairs [29]. Research to calculate more accurate nominal tooth root stress by taking the actual contact ratio into account [30], serves as the guideline of coupled analysis of thermo-mechanical gear study.

However, very few researches on gear flash temperature affected by dynamic load have been yet reported. This paper includes the varying transient thermal pattern of all nodes' temperature in any engaging period. The method has still not been seen in other researches. Another objective of this paper is sensitivity analysis that calculates and compares flash temperatures of gears influenced by dynamic load and multiple operating factors as well as different gear profiles parameters. Through the research and experiment of this paper, its results provide a more accurate reference for calculating and checking the scoring and bearing capacity of gears.

2. Governing theories and equations

2.1. Heat transfer model

The analysis of temperature field is based on the thermal balance equation of conservation of energy principle [31]. Heat transfer model and thermal boundary conditions are given to calculate the node temperature distribution and relative physical parameters of the gear system. The thermal analysis of gears strictly follows the first law of thermodynamics, namely the conservation of energy principle.

Assuming there is an isotropic three-dimensional heat conduction system with heat source (or cold source) inside, its thermal conductivity λ , specific heat c and specific gravity γ . The element is as Fig. 1. Q is the quantity of heat, the subscripts standing for different coordinate directions.

The heat transfer model considered in this paper is linear with no variation with temperature of the concerned material physical properties, and with potential heat source. Since thermal analysis of gears does not involve changes in kinetic energy or potential energy, the transient heat conduction equation (31) is presented in Eq. (1), where θ is temperature, t is time.

$$\frac{\partial \theta}{\partial t} = \frac{\lambda}{\gamma c} \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} \right) \quad (1)$$

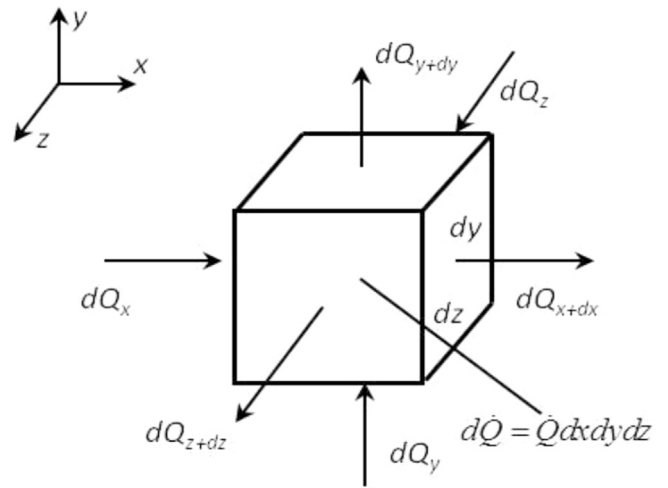


Fig. 1. Heat conduction model of the three-dimensional element.

2.2. Theories of instantaneous temperature rise on gear tooth surface

The instantaneous temperature rise on gear tooth surface is of vital importance to its capability to resist scuffing [32]. In the calculation of two contact faces with relative sliding velocity, assumptions are made:

- (1) Compared with contact area, the size of the sliding object is considered as infinite;
- (2) There is no heat radiation to surrounding media, which means all heat is transferred to the heat of the sliding object;
- (3) The pressure distribution of the contact zone follows the pattern of a parabola.

Suppose there are two infinitely long round rollers with relative sliding velocity, the width of the contact area between them being $2b$ (as Fig. 2). The friction of the contact area causes heat. If the friction coefficient is a fixed value, then the heat flux density along the width of $2b$ is the same with the pressure distribution pattern. The heat intensity, which equals the amount of heat generated by the heat source on a unit area in a unit time, is q . Suppose the unit thermal power of the heat source is a constant value, as the roller slides at a constant speed of v perpendicular to axis, there comes a sliding heat source with constant unit thermal power, which is shown in Fig. 2.

The heat intensity along the width of $2b$ is

$$q = q_{max} \left(1 - \frac{x^2}{b^2} \right) \quad (2)$$

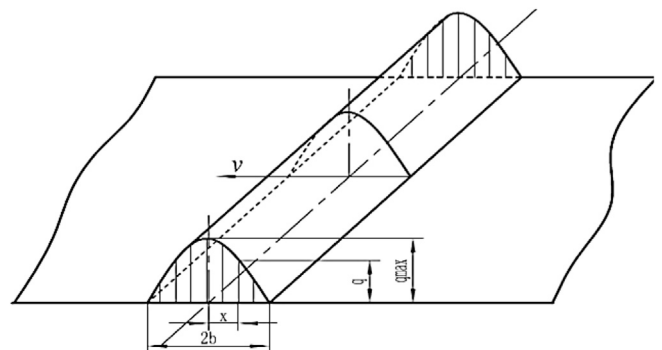


Fig. 2. Heat distribution of the contact zone.

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